ENVIRONMENTAL CONTROLS ON SOIL FROST ACTIVITY IN THE WESTERN CAPE MOUNTAINS, SOUTH AFRICA

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ABSTRACT

This study aims to analyse the environmental controls on soil frost processes in the Western Cape mountains of South Africa. Two microclimatic monitoring stations were established on different substrates at about 1900 m a.s.l. recording air and soil temperature, soil moisture and precipitation over periods of five and two years respectively. Other data available are snow cover estimations and soil textural data.

Results show the region to experience surficial diurnal frost only. The frequency of effective frost days in the sandstone areas is extremely limited due to insulation by snow cover and vegetation, effectiveness of the zero-curtain effect and high albedo values of the surface. Irrespective of climatic controls, sandstone-derived sediments are found to be too coarse to develop segregation ice. These strata underlie over 90 per cent of the Western Cape mountains over 1000 m a.s.l. Monitoring on shales indicates 12 and 16 diurnal frost cycles for needle-ice growth for 1993 and 1994, respectively.

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KEY WORDS: soil frost; needle-ice; environmental controls; Mediterranean mountains

INTRODUCTION

Field observations on active frost processes in the Western Cape mountains have shown the presence of micropatterned ground and turf- and stone-banked steps and lobes in argillaceous sediments at sites above 1600 m a.s.l. (Boelhouwers, 1995). However, soil frost features appear largely absent in the sandstone-derived debris mantles that dominate the mountains. First indications are that soil texture plays an important control on the spatial distribution of soil frost features in this region. In this paper a more comprehensive data record on relevant environmental parameters is presented to arrive at a synthesis of the various controls on current frost action in sediments for these mountains.

In assessing the controls on the contemporary soil frost processes, both climatic factors and material properties must be considered (Washburn, 1979; Williams and Smith, 1989; Krantz, 1990). Material properties relate particularly to the frost susceptibility of the sediment and are evaluated in Boelhouwers (1995). Climatic factors controlling the effectiveness of formation of ground frost features include intensity, frequency and duration of freeze/thaw cycles and soil moisture availability during these cycles. A description of the climatic controls on soil frost potential required the direct measurement of these parameters. To this effect two data-logger stations were established in the summit region of the Waaihoek mountains, at Waaihoek Peak and Mount Superior, respectively (Figure 1).

THE MONITORING SITES

The study area is situated at 33°30′S, 19°30′E and comprises the summit region of the Waaihoek range and the western part of the Hex River mountains near Mount Superior (Figure 1). This area ranges between 1600 and 1948 m a.s.l. The folded mountains of the southwestern Cape are built of quartzitic sandstone with occasional narrow bands of argillaceous strata, classified as part of the Cape Supergroup (SACS, 1980).

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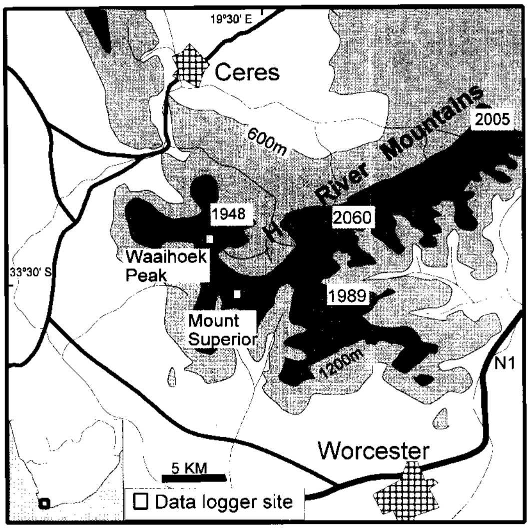

Figure 1. Location of the monitoring sites in the Western Cape mountains (altitudes in metres)

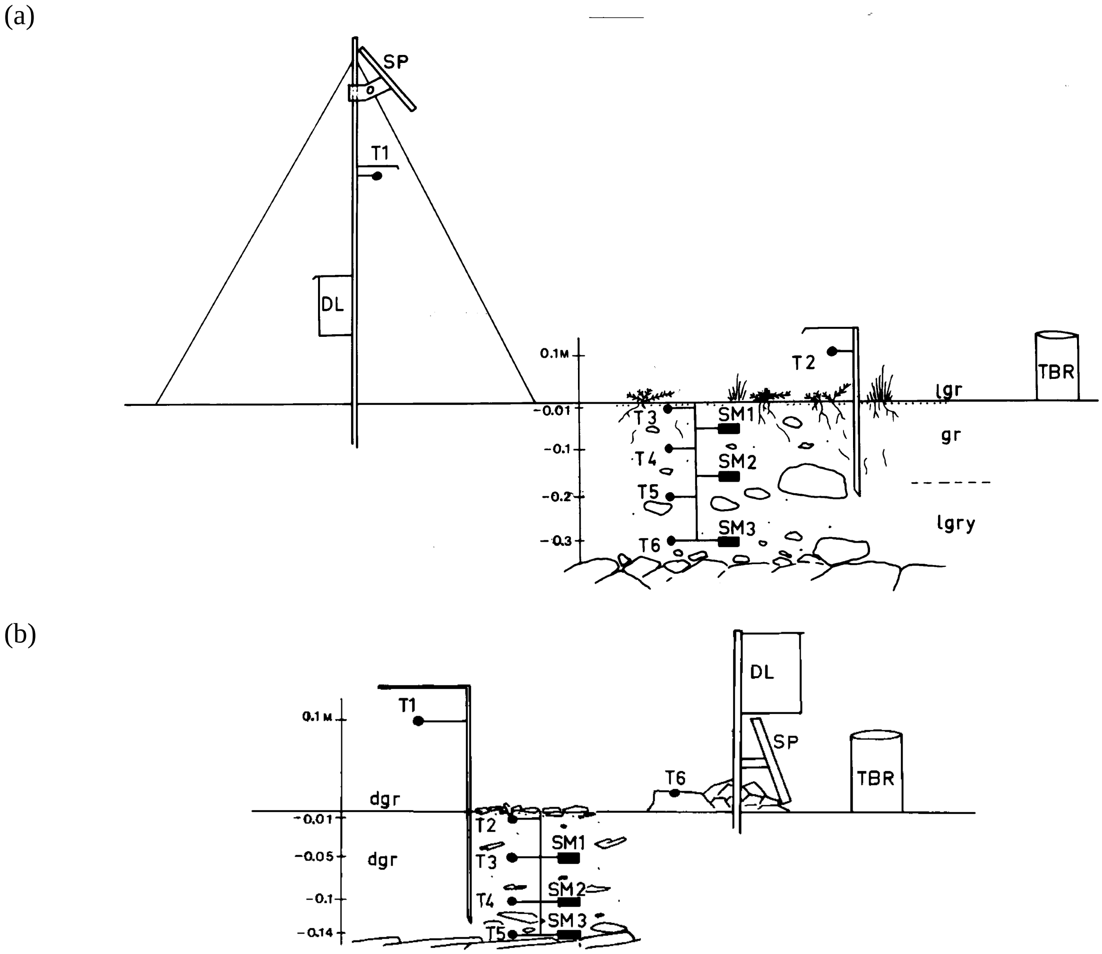

Figure 2. Site characteristics and location of sensors at the monitoring sites: (a) Waaihoek Peak (1900 m a.s.l.) and (b) Mt Superior (1850 m a.s.l.). Key: SP – solar panel; DL – data logger; T1–6 – temperature sensor; SM1–3 – soil moisture sensor; TBR – tipping bucket raingauge. Soil color codings: lgry – light grey; gr – grey; dgr – dark grey; lgry – light grey–yellow

Waaihoek Peak

The Waaihoek Peak monitoring site is positioned on the southeast extension of a small summit plateau at 1900 m. The station stands on a 4–5° slope with an aspect of 140° and is underlain by steeply dipping quartzitic sandstone of the Peninsula Formation. The shallow sandy soil reaches a thickness of 0·35 m and supports a poor vegetation cover of *Restio* (Cape reeds) species up to 0·2 m high. No active frost features are found on these sandstone slopes. Terracettes, however, are present in valleyheads and where clast abundance in the debris mantles is low.

Locally manufactured MCS data-loggers were used for this project. The physical structure of the stations and the type and position of sensors maintained between 7 January 1990 and 31 December 1994 are described in Figure 2a. All sensors were calibrated according to the manufacturer's instructions (Mike Cotton Systems, Cape Town). Soil moisture was monitored by means of nylon resistance blocks consisting of an inner mesh electrode wrapped in nylon material, and an outer mesh electrode enclosing the sensor (Bouyoucos, 1949). This sensor is calibrated by setting the sensor value at zero when it is air-dry. A value of 100 is assigned to a sensor in fully saturated condition. Tipping bucket raingauges with a bucket capacity of 0·2 mm were used to record precipitation. Daily records were kept, including maximum and minimum temperature and 24 h precipitation totals. Average daily soil moisture levels were recorded only as the range between daily maximum and minimum values proved to be minimal.

Mount Superior

A second data-logger site was established on 1 May 1993 to provide microclimatic data from a site with a different substrate and currently active soil-frost processes. The Mount Superior station is positioned 5 km SSE of the Waaihoek Peak site on a flat summit plateau of Cederberg shale at 1860 m elevation. The surface cover comprises fractured bedrock and bare shallow soil with occasional tussocks of *Restio* spp. up to 0·5 m high. Active patterned ground is abundant on this summit, while stone- and turf-banked steps and lobes are widespread on the north- and south-facing slopes (Boelhouwers, 1995). The instrumentation set-up is described in Figure 2b and was similar to that used for the Waaihoek Peak site. The soil temperature and moisture sensors were placed in a bare sediment of 0·15 m depth. Daily maximum and minimum temperatures were recorded for each sensor as well as daily average relative soil moisture levels and precipitation totals.

THE TEMPERATURE RECORD

Vertical temperature profiles

The vertical temperature profiles presented in Figure 3 offer a first general characterization of the thermal regimes at the two microclimatic stations. The profiles, constructed from the averaged monthly and yearly values, illustrate the commonly observed trend of highest temperature ranges close to or at the soil surface (Figure 3) (cf. Oke, 1987). At Mt Superior the level of predominant heat exchange corresponds with the soil surface. At Waaihoek Peak, greatest heating is experienced at the soil surface in summer, but nocturnal heat exchange throughout the year is greatest at 0·1 m above the soil surface. This radiation buffering in the summer temperature profile suggests that it is a function of the sparse vegetation cover at the monitoring site. Both vegetation and snow cover may moderate soil surface maxima and minima in winter. The occurrence of the greatest heat exchange somewhat above and not at the soil surface may significantly reduce the soil frost frequency and intensity experienced at the Waaihoek site.

Frequency and intensity of freeze/thaw cycles

Monthly and annual totals of frost frequency and intensity were calculated from the daily temperature record for each year (Tables I and II). It must be noted that the averaged values are influenced by the variable length of record per sensor and month.

Waaihoek Peak. From the record in Tables I and II it appears that only diurnal freeze/thaw cycles occur in the soil. Frost penetration appears restricted to the upper 0·1 m of the soil, in agreement with studies in other diurnal

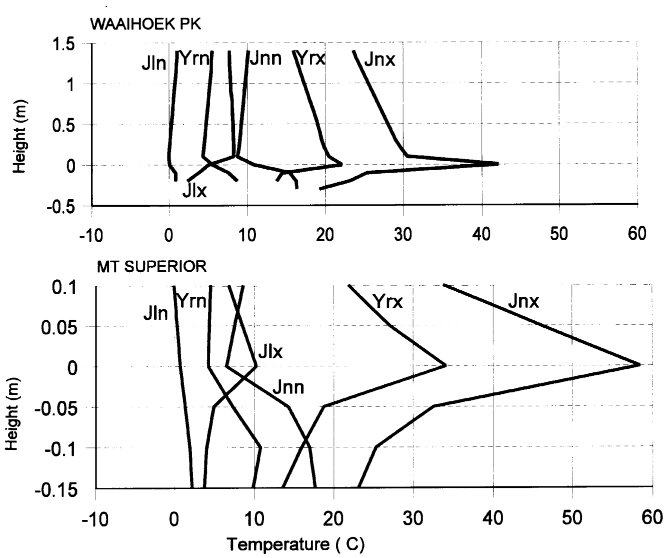

Figure 3. Vertical temperature profiles for Waaihoek Peak and Mt Superior. Note the different vertical scales for the two sites

Table I. Average number of days with temperatures below 0°C at Waaihoek Peak (1990–1994) and Mt Superior (1993–1994)

	Waaihoek Pk (1990–1994)					Mt Superior (1993–1994)				
Month	+1·5 m	+0·1 m	–0·01 m	–0·1 m	–0·2 m	+0·1 m	–0·01 m	–0·05 m	–0·1 m	–0·14 m
Jan.	0	0	0	0	0	0	0	0	0	0
Feb.	0	0	0	0	0	0	0	0	0	0
Mar.	0	0·2	0	0	0	0	0	0	0	0
Apr.	2·8	4·4	0	0	0·7	3	3	0	0	0
May.	5·8	8·9	5	0	0	6·5	9	0	0	0
Jun.	15·4	12·3	15·6	8·3	0	14	10·5	0	0	0
Jul.	10·9	17·6	24·6	12·6	0	18	3·5	0	0	0
Aug.	12·6	15·4	18·1	10·3	0	15·5	16	0	0	0
Sep.	7·9	9·3	9·8	3	0·5	10·5	8	0	0	0
Oct.	4·7	6	1	1·3	0	4	4·5	0	0	0
Nov.	1	1	0	0	0	4·5	6	0	0	0
Dec.	1	1	0	0	0	1	0·5	0	0	0
Year	62·1	76·1	74·1	35·5	1·2	77	61	0	0	0

frost action environments (e.g. Gradwell, 1954; Fahey, 1973; Pérez, 1984). A high interannual variability in number of frost days in winter is apparent from the five year record, ranging between 0 and 27, 14 and 31, and 9 and 19 for June, July and August respectively. The duration of the frost season runs from May to September at the soil surface (–0·01 m), but shortens in length and decreases in intensity with depth below the surface. Frost intensity, as measured by monthly frequency totals of minimum temperatures reached, is summarized in Table II. It is evident that the lowest temperatures, down to between –6 and –8°C, are recorded in the air, but are limited to values between 0 and –2°C at, and below, the soil surface.

Mount Superior. Diurnal freeze/thaw cycles were recorded at Mt Superior from April to November, both at 10 cm above the ground and at the soil surface (Table I). No frost cycles were recorded beneath the soil surface. The total number of frost days in 1993 and 1994 at +0·1 m compare well with those at Waaihoek Peak, but this is not the case for the monthly frost frequency records at the soil surface. A high interannual variability in number of freeze/thaw cycles is also noted for the Mt Superior site. Although frost penetration at Mt Superior appears to be less, frost intensity at the soil surface is higher than that recorded at Waaihoek Peak. Temperatures between –2 and –6°C make up an important percentage of the total number of frost days (Table II).

Table II. Annual frost frequency and intensity at Waaihoek Peak and Mt Superior

	Waaihoek Pk (1990 – 1994)				
Month	+1·5 m	+0·1 m	–0·01 m	–0·1 m	–0·2 m
1990 (n=170)					
<–8	0	0	0	0	0
–8 – <–6	0	0	0	0	0
–6 – <–4	0	2	0	0	0
–4 – <–2	0	9	0	0	0
–2 – <0	0	20	15	0	0
Total	0	31	15	0	0
1991 (n=157)					
<–8	0	—	0	—	—
–8 – <–6	1	—	0	—	—
–6 – <–4	12	—	3	—	—
–4 – <–2	20	—	12	—	—
–2 – <0	28	—	80	—	—
Total	61	—	95	—	—
1992 (n=301)					
<–8	0	0	0	0	—
–8 – <–6	6	2	0	0	—
–6 – <–4	12	7	0	0	—
–4 – <–2	17	26	0	0	—
–2 – <0	33	54	79	2	—
Total	68	89	79	2	—
1993 (n=323)					
<–8	0	1	0	0	0
–8 – <–6	2	1	0	0	0
–6 – <–4	5	6	0	0	0
–4 – <–2	8	11	0	0	0
–2 – <0	22	40	36	0	2
Total	37	59	36	19	2
1994 (n=344)					
<–8	0	0	0	—	0
–8 – <–6	3	0	0	—	0
–6 – <–4	6	8	0	—	0
–4 – <–2	23	30	0	—	0
–2 – <0	27	52	77	—	1
Total	59	90	77	—	1

	Mt. Superior				
Month	+0·1 m	–0·01 m	–0·05 m	–0·1 m	–0·14 m
<–8	2	0	0	0	0
–8 – <–6	2	1	0	0	0
–6 – <–4	3	7	0	0	0
–4 – <–2	16	8	0	0	0
–2 – <0	37	66	0	0	0
Total	60	82	0	0	0
1994 (n=365)					
<–8	0	0	0	0	0
–8 – <–6	0	1	0	0	0
–6 – <–4	6	10	0	0	0
–4 – <–2	30	13	0	0	0
–2 – <0	55	27	0	0	0
Total	91	51	0	0	0

— indicates no record

Implications for soil frost activity

It is well known that the 0°C boundary does not necessarily correspond with the freezing point of soil water (e.g. French, 1988). As frost intensity at the monitoring sites is limited, particularly at Waaihoek Peak, any depression of the freezing point may greatly affect local soil frost potential.

The dissolution of salts in soil water may cause soil water to start freezing at temperatures somewhat below 0°C. Natural salt concentrations in soil water are, however, considered so weak that this normally lowers the freezing point by only 0.1°C (Williams and Smith, 1989). Further, soil moisture adsorption and capillary suction in soil pores may result in considerable amounts of unfrozen water in soils at temperatures below 0°C. Although it was not possible to establish the freezing point of water for the two local soils, even a depression in the freezing point of only 0·1°C does reduce the number of effective frost days by about 10 per cent at both sites (Boelhouwers, unpublished data).

Environments subjected to diurnal frost cycles only are characterized by ice segregation in the form of ice needles at the soil surface (e.g. Gradwell, 1954; Mackay and Mathews, 1974; Pérez, 1984). Outcalt (1971) observed that temperatures of at least –2°C are required to start needle-ice growth, a value which appears to be considered generally applicable (Lawler, 1988).

The soil temperature record from Waaihoek Peak registered 15 days with temperatures below –2°C during 1991 only (Table II). Potential for effective freeze/thaw cycles thus appears to be very limited for the Waaihoek Peak site even for needle-ice growth. On the other hand, nocturnal temperatures at Mt Superior reached between –2 and –6°C on 16 days during 1993 and 24 days in 1994 (Table II). This suggests that the potential exists for a limited number of days with needle-ice growth at this site, annually.

PRECIPITATION AND SOIL MOISTURE

Precipitation

Daily precipitation totals were monitored at Waaihoek Peak from 1991 to 1994 and at Mt Superior from 1993 to 1994. Annual totals amounted to 2488 mm at Waaihoek Peak, 77 per cent of which fell during the freeze/thaw season from May to September. Annual precipitation at Mt Superior amounted to 1100 mm with a seasonal distribution similar to Waaihoek Peak.

Snow

No direct observations on snow cover could be made over the winter season, except during occasional visits for data-logger maintenance. Two sources of data do, however, allow for estimation of snowfall frequencies and duration of snow cover. First, logbook entries at Hoare Hut were checked for the period 1972–1994 for reports on snowfall and the presence of a snow cover in the Waaihoek Peak area (see Boelhouwers, 1991, figure 4). As the hut is mainly occupied during weekends and holiday periods, an underestimation of the total number of snowdays (days with snowfall and/or snow cover) can be expected. The record indicates an average of 31·4 snowdays per year.

A second method to estimate the duration of snow cover is based on interpretation of the impact of snow cover on soil surface temperatures. The insulating effect of snow has been shown to reduce diurnal temperature ranges beneath a snow cover to values between –1·0 and +1·0°C (Thorn, 1979; Hall, 1980). In this study, snow cover could readily be associated with days during which diurnal temperatures ranges are below 4°C and have values consistently between +4°C and –1°C.

Estimation of snow cover duration at Mt Superior shows the presence of snow during essentially the same periods as at Waaihoek Peak, although there is poor correspondence in daily patterns (Figure 4). The total number of snowdays obtained from the temperature records is very similar for the two stations. From the records it appears that snow is a common feature from mid-May to the end of September with occasional falls in April and October. First snows tend to melt within one or two days but may remain for up to three weeks in the period from July to September.

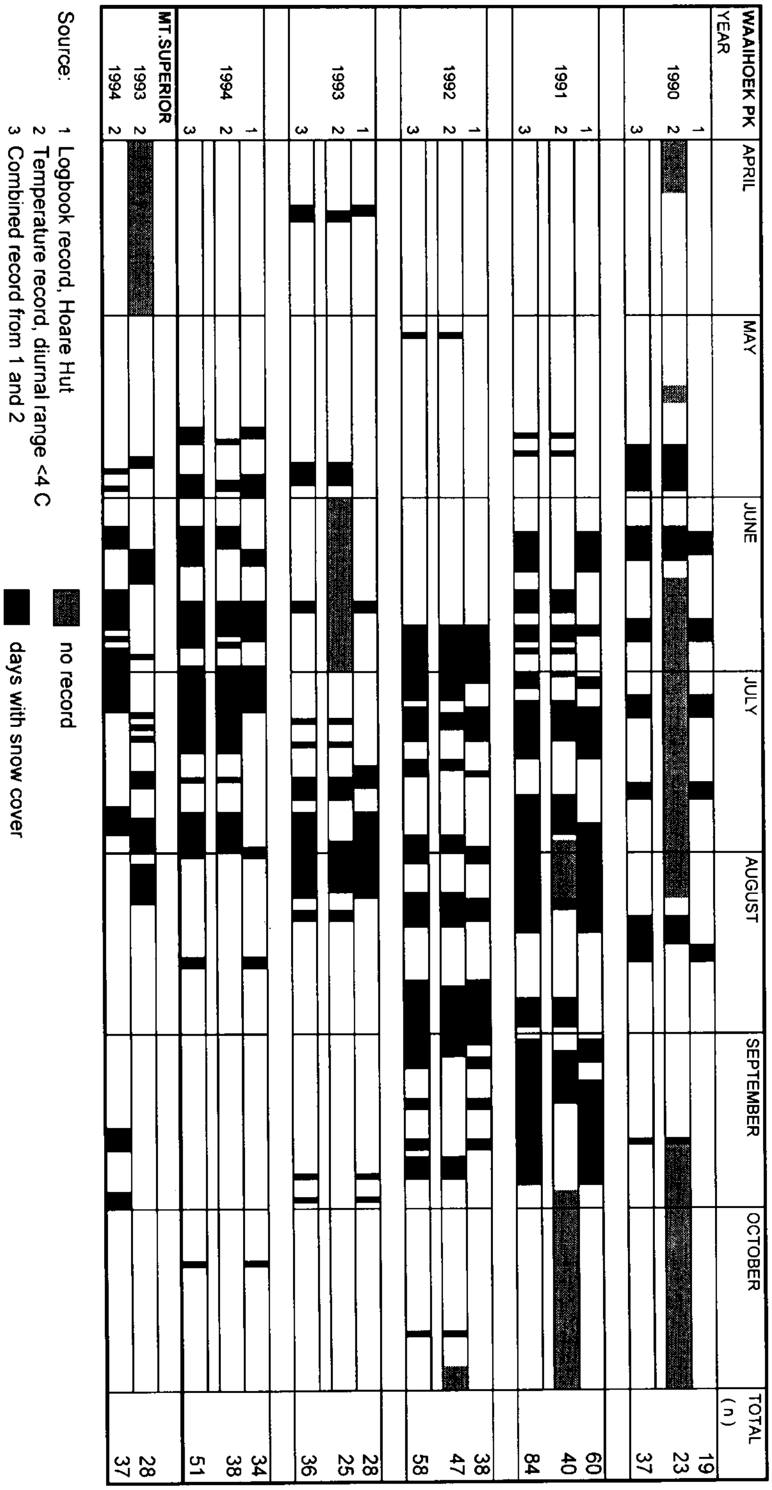

Figure 4. Snow cover duration estimations at Waaihoek Peak and Mt Superior, based on (1) logbook entries at Waaihoek Peak, (2) soil surface temperature ranges, and (3) the record combined from (1) and (2)

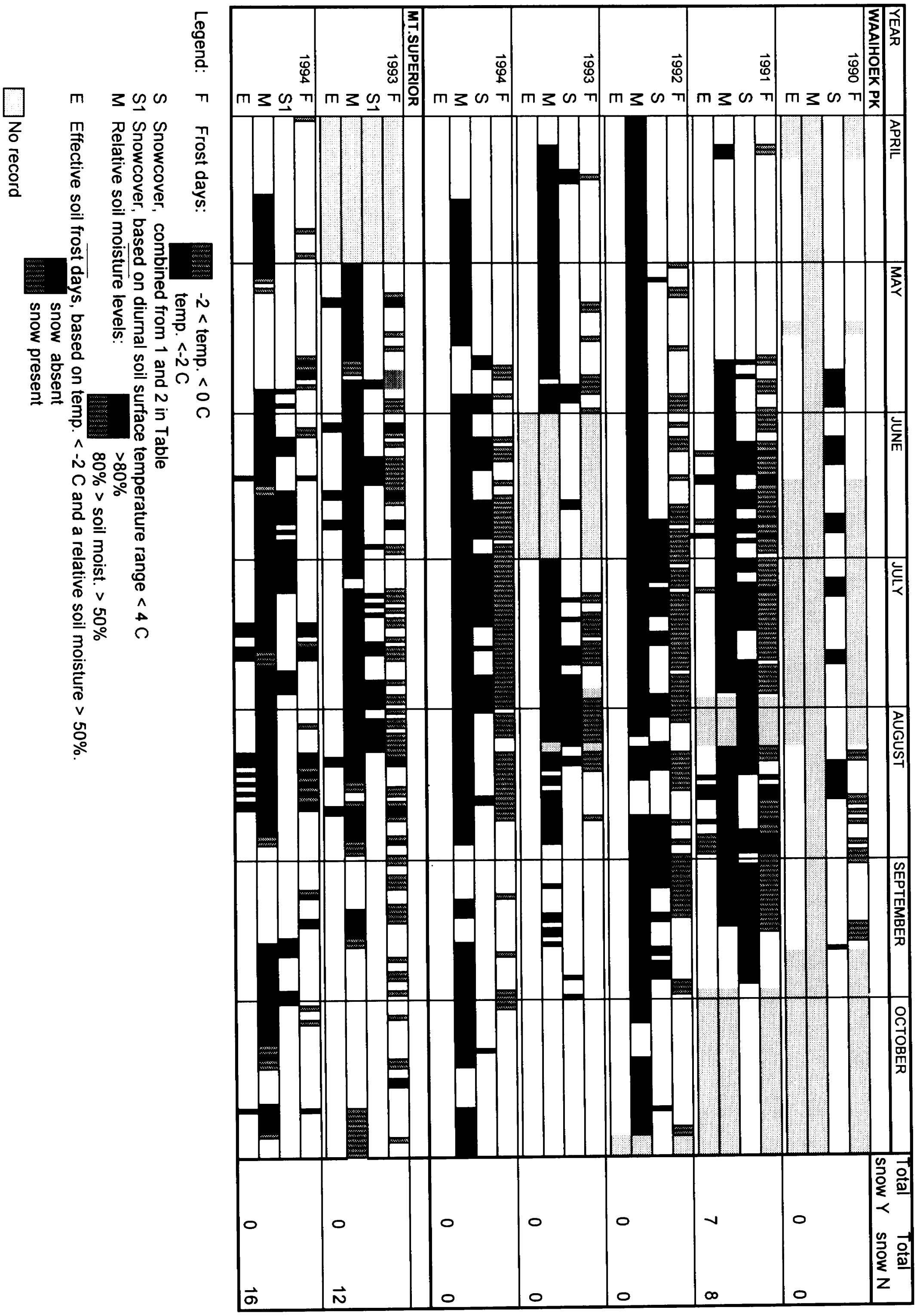

Figure 5. Frequency of effective soil frost days at Waaihoek Peak (1990–1994) and Mt Superior (1993–1994). See text for further explanation

Based on the combined record of days with snow cover for 1991–1994, it is estimated that 57 per cent of frost days at Waaihoek Peak are associated with snow (rows F and S in Figure 5). On these days snow cover maintains soil surface temperatures near 0°C and inhibits temperature amplitudes sufficient for effective soil frost activity. At Mt Superior, soil frost activity is reduced in a similar manner, but effective freeze/thaw cycles occur from May to October when snow is absent.

Soil moisture

Typical results of the direct measurement of relative soil moisture levels are presented in Boelhouwers (1995). During the summer months, relative soil moisture levels drop to less than 10 per cent at 5 cm depth at Waaihoek Peak and approach 0 per cent at the same level in the 0·14 m thick sediment at Mt Superior. Late summer and autumn rainfall of 50 mm/day produces rapid near-saturation of soils at Waaihoek Peak. The significantly lower diurnal totals at Mt Superior are insufficient to raise the water content above 10 per cent until the onset of the autumn and winter rains.

Both the Waaihoek Peak and Mt Superior record indicate soil moisture levels generally above 80 per cent throughout the rainy season from April to November (rows M in Figure 5). The soils maintain high saturation levels in winter as a result of the high number of precipitation days, the high absolute amounts received, particularly at Waaihoek Peak, and the frequent snow cover.

FROST SUSCEPTIBILITY OF THE SOIL MATERIALS

Soil texture

A distinction needs to be made between soils derived from the quartzitic sandstone strata of the Peninsula Formation and those derived from the Cederberg shale. Soil samples were collected from the A horizon at a depth between 5 and 10 cm below the surface at a variety of sites near Mt Superior ($n=6$) and Waaihoek Peak ($n=25$). Results of particle size analysis of the fraction smaller than 2 mm are presented in Boelhouwers (1995). For sandstone-derived soils the fraction of fines (fraction <64 μm) ranges between 2 and 7 per cent, and between 18 and 45 per cent for the shales.

Soil moisture and texture implications for needle-ice growth

The influence of soil texture on minimum soil moisture levels required for needle-ice growth were experimentally established by Meentemeyer and Zippin (1981, figure 3, p. 119). The sandy soil at the Waaihoek logger site contains 4–5 per cent fines and 21·5 per cent (dry weight) moisture at saturation. When tested against the relationships found by Meentemeyer and Zippin (1981, p. 119), the sediment is found too coarse, even under saturation, to develop ice needles. On the other hand, the sediment at the Mt Superior logger site is highly frost-susceptible, containing 24 per cent fines and attaining water saturation at 44 per cent (dry weight). Meentemeyer and Zippin (1981) achieved needle-ice growth in a soil with 24·1 per cent fines at a minimum soil water content of 19·5 per cent. Similar critical soil moisture values for comparably textured soils were obtained by Outcalt (1971) and Pérez (1984). For the Mt Superior site this converts to a relative soil moisture content of 45–50 per cent. Relative soil moisture levels at Mt Superior are predominantly above 50 per cent during the freeze/thaw season from April to November (Figure 5).

The data-logger record from Mt Superior suggests that the soil water content in the sandy loam at this site is favourable for needle-ice formation during most of the freeze/thaw season. In contrast, even under saturation the sandy soils at Waaihoek Peak are not frost-susceptible.

FIELD OBSERVATIONS: GROUND AND SURFACE ICE IN SANDSTONE-DERIVED SEDIMENT

No field evidence for segregation ice growth or needle-ice could be observed in the coarse debris mantles at Waaihoek between January 1990 and December 1994. In contrast, saturation overland flow due to snowmelt and heavy rainfall is of common occurrence in winter. Freezing of this surface water can be observed to form an ice-crust at the soil surface. Water may continue to trickle downslope beneath this frozen water surface. In other

cases, pore-ice formation in saturated soils can readily be observed in winter on summit plateaus, near stream banks or other sites where shallow soils are in close vicinity to bedrock.

The zero-curtain effect

The effect of latent heat maintaining temperatures near 0°C over extended periods in freezing or thawing soils has been referred to as the ‘zero-curtain effect’ (Washburn, 1979; French, 1976). The freezing of water at the surface of saturated soils implies that, as elsewhere, significant amounts of latent heat are released when freezing temperatures are reached in the Waaihoek Peak area. Throughflow and overland-flow further increase sensible and latent heat supply near the soil surface. The difference in minimum temperatures reached in the air at +0·1m, compared to the soil surface, as noted above, is best explained by the effective compensation of sensible heat loss from the soil surface by latent heat release from the freezing of abundant soil moisture.

Conditions in the arenaceous sediment of the Waaihoek Peak area appear particularly favourable for the zero-curtain effect to be effective. High soil moisture levels prevail during most of winter and freezing rates are sufficiently slow that they do not overcome the latent heat release within a single diurnal frost cycle. This effect restricts frost penetration beyond the soil surface and maintains soil surface temperatures around the freezing point.

CONCLUSIONS

The summit areas of the Mediterranean mountains of the Western Cape experience a mean annual air temperature of around +10°C. Under this temperature regime only surficial, diurnal frost cycles occur from May to September. Despite an average of 74 frost days a year at Waaihoek Peak, no field evidence in favour of frost-induced soil processes could be observed. On a regional scale, the general paucity of geomorphological evidence for soil frost activity is striking. The following environmental controls were identified to explain the absence of frost-related landforms.

(1) Over 90 per cent of the Western Cape mountains are underlain by arenites of the Table Mountain Group. Particle size analysis indicates that the sediments derived from these lithologies are too coarse to allow for the formation of segregation ice. This means that irrespective of climatic controls, sediment properties do not allow for soil frost features to develop over most of the Western Cape mountains.

(2) Needle-ice growth requires a soil surface temperature of at least −2°C (Outcalt, 1971; Lawler, 1988). The frequency of frost days which meet this criteria is extremely small due to the following factors.

- (a) High precipitation values in winter result in the presence of snow on an estimated 31 days per year. On 57 per cent of the frost days, recorded temperatures remained between 0 and −2°C due to the presence of snow.
- (b) The presence of vegetation raises the plane of greatest heat exchange above the heat surface which effectively reduces the diurnal temperature extremes experienced at the soil surface.
- (c) High soil moisture levels and the occurrence of overland flow imply that significant amounts of latent heat are released when freezing temperatures are reached. The zero-curtain effect is suggested to be particularly effective in controlling frost intensity in the Western Cape mountains.
- (d) Higher albedo values for the light-coloured sandstone surfaces result in less effective radiation exchange with the atmosphere, reducing frost frequency–intensity in these materials, relative to darker-coloured shales.

High soil moisture levels are maintained throughout the cold season and form no limiting factor to effective soil frost activity in the region.

It appears that the explanation for the difference in frost activity between the two sites is, despite some differences in climatic parameters, mainly given by the differences in material properties at the two sites. The coarse sediment textures associated with the Table Mountain Group arenites do not only allow for pore ice and no segregation ice has been observed.

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